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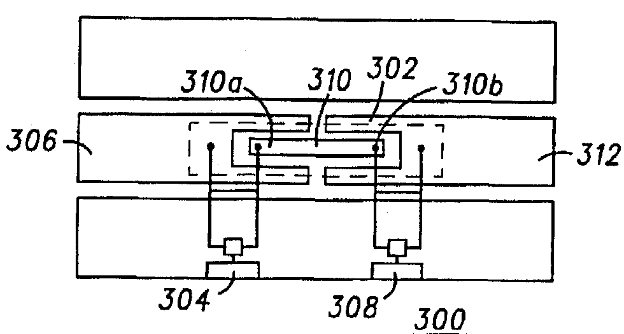
(54) **Title:** SWITCHABLE AND TUNABLE COPLANAR WAVEGUIDE FILTERS



(57) Abstract: A series of switchable and tunable filters are provided. The filters are manufactured using coplanar waveguide fabrication techniques and micro-electro- mechanical system switches. This results in smaller filters that can be either switched between a band pass filter and a low pass filter or switch between operating ranges.

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SWITCHABLE AND TUNABLE COPLANAR WAVEGUIDE FILTERS

Technical Field of the Invention

This invention relates to the field of resonators and filters and more specifically to switchable and tunable coplanar waveguide resonators and filters using micro-electro-mechanical switches.

Background of the Invention

A need exists for switchable and tunable filters for both wideband and multiband communication systems that are small in size, inexpensive and easy to manufacture. Prior art switchable/tunable filters use resonant ring arrangements with diodes used as switches to select filter response. These diode switches tend to be large in size and expensive. To help alleviate this problem, attempts have been made to manufacture filters using a micro-electro-mechanical system method. This leads to a switchable filter system but requires two different filter structures to be built with a diode for use as a switch to switch the signal path from one filter structure to another. Drawbacks to this design include that the process used to make these filters is complicated, that the resultant filter structure is large, and that there is interference between the two filter structures.

Another approach is to use coplanar waveguide filters. Coplanar waveguide filters are manufactured by

using a substrate covered with a metal layer. The metal is etched to layout various filter configurations. While small filters can be manufactured in this manner, a switchable filter system still requires two different filters connected by a diode switch. This results in a large structure.

What is needed is a filter that can combine both coplanar waveguide filters with micro-electro-mechanical switches.

Brief Description of the Drawings

For a more complete understanding of the present invention and advantages thereof, reference is now made to the following descriptions, taken in conjunction with the following drawings, in which like reference numerals represent like parts, and in which:

FIGURE 1 illustrates an interdigital capacitor;

FIGURE 2 illustrates an interdigital inductor;

FIGURE 3 illustrates a switchable filter in accordance with the teachings of the present invention;

FIGURE 4 illustrates a second embodiment of a switchable filter in accordance with the teachings of the present invention;

FIGURE 5 is a graph illustrating the filter characteristics of the switchable filter of FIGURE 4;

FIGURE 6 illustrates a tunable filter in accordance with the teachings of the present invention;

FIGURE 7 is a cross-sectional view of FIGURE 6 illustrating the formation of the capacitor; and

FIGURE 8 is a graph illustrating the filter characteristics of the tunable filter of FIGURE 7.

Detailed Description of the Drawings

The present disclosure discusses switchable and tunable filters that overcome the disadvantages of the prior art. Coplanar waveguide filter configurations and micro-electro-mechanical systems switch technology are combined on the same circuit to provide switchable and tunable filters. This is advantageous because device performance in coplanar waveguide structures is insensitive to substrate thickness. Also, coplanar waveguide filters with micro-electro-mechanical system switches are less expensive then prior art micro-electro-mechanical system filter banks. Additionally, in the present invention a single circuit can provide either two different filter responses selectable by micro-electro-mechanical system switches or a single filter with a tunable response.

A preferred embodiment of the micro-electro mechanical systems switch is disclosed in US patent application titled MICRO-ELECTRO MECHANICAL SWITCH, filed on February 1, 2000 by Sun et al. And identified as S/N 09/495,664. Further information concerning these switches is provided in US patent application titled MICRO ELECTRO MECHANICAL SYSTEM DEVICE filed on February 1, 2000 by Huang et al. and identified as S/N 09/495,786. These applications explain in detail how these switches are made, used and for example activated. Both of these applications are incorporated herein by reference. In

order to avoid confusion no further discussion of these switches is included herein.

Turning to FIGURE 1 and FIGURE 2, these figures illustrate two basic circuit elements in coplanar waveguide structures. FIGURE 1 illustrates interdigital capacitor 100. In general coplanar waveguide structures are formed on a substrate having a metal layer on top. On either side of interdigital capacitor 100 are ground strips 102. Adjacent to ground strips 102 are two gaps, a first gap 104 and a second gap 106. These gaps are formed by etching the metal layer away to expose the substrate. Typically the substrate is comprised of resistive silicon although other substrates such as glass can be used. The metal layer is typically comprised of gold or aluminum although other materials can be used. The finger structured gap 108 separates the input signal line 110 and output signal line 111.

FIGURE 2 illustrates an interdigital inductor 200. Shown are ground strips 202, 204, signal input line 206 and signal output line 207. As in the interdigital capacitor, first gap 210 and second gap 212 run the length of inductor 200 to separate the ground strip from input signal lines 206 and output signal line 207. In the inductor, the input signal line 206 and the output signal line 207 are connected by the central metal line 214. This structure forms a coplanar waveguide inductor.

FIGURE 3 illustrates a switchable filter in accordance with the teachings of the present invention.

Switchable filter 300 comprises a filter element 302. In one embodiment, filter element 302 is essentially rectangular in shape. This shape is formed by etching a rectangle in the metal layer leaving a central metal segment 310 having a first part 310a and a second part 310b. While a rectangular filter element is shown, it would be obvious to one skilled in the art that a variety of shapes can be substituted. A first micro-electro-mechanical system switch 304 is operable to connect first part 310a of central metal segment 310 with signal input line 306 when closed. A second micro-electro-mechanical system switch 308 connects the second part 310b of central metal segment 310 with the signal output line 312. If first micro-electro-mechanical system switch 304 is open, signal input line 306 and central metal segment 310 will not be connected and will be separated by the material of the substrate. This portion of filter 300 will act as a capacitor and resembles the structure in FIGURE 1. If first micro-electro-mechanical system switch 304 closes, signal input line 306 and central metal segment 310 are electrically connected and a signal passes from the signal input line 306 to central metal segment 310 while passing by dielectric lines formed by the filter structure 302. When first micro-electro-mechanical system switch 304 is closed this segment acts like an inductor and resembles the structure of FIGURE 2.

On the other side of filter element 302, second micro-electro-mechanical system switch 308 operates in a

similar manner. If second micro-electro-mechanical system switch 308 is open, the second part of filter structure 302 operates as a capacitor. If second micro-electro-mechanical system switch 308 is closed, it operates like an inductor as seen in FIGURE 2.

First micro-electro-mechanical system switch 304 and second micro-electro-mechanical system switch 308 are compatible with the coplanar configuration of coplanar waveguide filters. This means the micro-electro-mechanical switches are fabricated on the same wafer and at the same time the coplanar waveguide filter elements are formed. In prior art switchable and tunable filters, after the filter was fabricated diode switches were added. This resulted in larger structures and increased fabrication costs.

Thus, the filter response in FIGURE 3 can be changed by opening or closing first micro-electro-mechanical system switch 304 and/or second micro-electro-mechanical system switch 308. For example, if both switches are closed, an inductor-inductor circuit element is formed. If both switches are opened, a capacitor-capacitor circuit is formed. If one switch is opened and one is closed, a capacitor-inductor circuit is formed. When the inductor-inductor circuit is formed, the switchable filter acts as a low pass filter. When both switches are open (a capacitor-capacitor circuit) the filter acts as a band pass filter. The series capacitors create a high pass segment but the balance of the co-planer waveguide

structure inherently has an upper frequency limit thereby creating a band pass filter. In both cases, the insertion loss is very low and can be further lowered by lowering the contact resistance of the micro-electro-mechanical system switches.

Therefore, FIGURE 3 illustrates a switchable filter having a compact design. With the settings of two switches, the filter behavior can be changed from a band pass filter to a low pass filter. This can be contrasted with the prior art filter which needed two separate filter structures, one low pass and one band pass and a diode switch to select which of the filters to use. The present invention allows for the use of a single filter element that can be used as two different types of filters.

FIGURE 4 illustrates an alternative embodiment of the present invention where a single switchable filter comprises multiple segments. Illustrated is a coplanar waveguide filter 402 comprising six segments connected to micro-electro-mechanical system switches.

Illustrated is a first segment 404 associated with a first micro-electro-mechanical system switch 406, a second segment 408 associated with a second micro-electro-mechanical system switch 410, a third segment 412 associated with a third micro-electro-mechanical system switch 414, a fourth segment 416 associated with a fourth micro-electro-mechanical system switch 418, a fifth segment 420 associated with a fifth micro-electro-mechanical system switch 422 and a sixth segment 426

associated with a sixth micro-electro-mechanical system switch 428. An input signal line 428 and an output signal line 430 provides a signal path through the FIG. 4 structure. The position of the micro-electro-mechanical system switches determines the characteristics of filter 402. For example, if first micro-electro-mechanical system switch 406 and second micro-electro-mechanical system switch 410 are open and the other switches are in the closed position, the filter 402 acts as a band stop filter. In a second embodiment, if the first micro-electro-mechanical system switch 406 and second micro-electro-mechanical system switch 408 are in the closed position and the other switches are in the open position, filter 402 acts as a band pass filter. While this example showed six segments attached to six micro-electro-mechanical system switches, this was for exemplary purposes only. Those skilled in the art will recognize that filters can be designed with any number of segments and switches.

FIGURE 5 is an exemplary graph 500 of the filter characteristics of filter 402. First curve 502 illustrates the filter response when the filter is operating as a band stop filter. Second curve 504 illustrates the filter response when the filter is operating as a band pass filter.

This embodiment illustrates that multiple filter elements can be combined to form switchable filters that operate in different frequency ranges or have different

filtering characteristics. While six filter elements were used in this example, it would be obvious to one skilled in the art to combine any combination of filter elements and micro-electro-mechanical system switches together for desired filtering characteristics.

FIGURE 6 illustrates a tunable filter 600 in accordance with the teachings of the present invention. Tunable filter 600 includes tunable filter element 602 with center metal segment 603, input signal line 604, output signal line 605, ground plates 606 and 608, first gap 610, and second gap 612. Also included are first capacitor 614, second capacitor 616, first micro-electro-mechanical system switch 618 and second micro-electro-mechanical system switch 620. Capacitors 614 and 616 are formed by applying a thin layer dielectric and a top metal electrode over the signal line metal 604 and 605 as shown in detail in FIGURE 7. These capacitors are processed at the same time with the micro-electro-mechanical system switches. First micro-electro-mechanical system switch 618 and second micro-electro-mechanical system switch 620 are operable to couple first capacitor 614 to center metal segment 603 and second capacitor 616 to center metal segment 603 when the switches are in the closed positions. When the switches are closed the capacitance of the circuit is increased.

In this embodiment, the central frequency of the band pass filter formed by the above design can be changed by connecting the capacitors 614 and 616 to center metal

segment 603 by closing switches 618 and 620. Thus the status of the switches (closed or open) determines the central frequency of the filter.

FIGURE 7 is a cross-sectional view of FIGURE 6 illustrating in more detail the structure of capacitor 614 (capacitor 616, while not illustrated in FIGURE 7, has a similar structure). Illustrated is signal input line 604, substrate 702, center metal segment 602 and capacitor 614. Capacitor 614 is formed by signal input line 604 with a thin layer of dielectric material 706 formed over the signal input layer 604. A top electrode 708 is formed over the dielectric material 706 to complete the capacitor. A micro-electro-mechanical system (not shown but illustrated in FIGURE 6 as 618) is operable to connect on top electrode 708 with center metal segment 603 in order to form the filter. One advantage of capacitor 614 as illustrated in this example is that it can be manufactured at the same time as the other components of the filter such as the micro-electro-mechanical system switch.

This behavior is illustrated in FIGURE 8. FIGURE 8 is a graph of the frequency response of tunable filter 600 of FIGURE 6 in accordance with the teachings of the present invention. A first curve 802 is for the embodiment where both switches are closed. In this embodiment, the capacitors are coupled to the central metal segment. Second curve 804 illustrates the embodiment where both switches are open. As can be seen

in FIGURE 8, when the switches are open (not connected to the capacitor) the central frequency of the filter is about 10.5 GHz. When the switches are closed, the central frequency shifts to 4GHz. The numbers shown are for illustration purposes only and will vary upon the use of different sized capacitors and filter element design.

Although the present invention has been described in several embodiments, a myriad of changes, variations, alterations, transformations and modifications may be suggested to one skilled in the art, and it is intended that the present invention encompass such changes, variations, alterations, transformations and modifications that fall within the spirit and scope of the appended claims.

What is Claimed

1. A switchable filter comprising:
at least one filter element having a central metal segment;
a signal input line;
a first micro-electro-mechanical system switch connected to the signal input line and a first end of the central metal segment;
a second micro-electro-mechanical system switch connected to the signal input and a second end of the central metal segment; and
wherein the position of the first micro-electro-mechanical system switch and the second micro-electro-mechanical system switch determines the filters characteristic.

2. The filter of Claim 1, wherein the filter acts as a band pass filter when both switches are open.

3. The filter of Claim 1, wherein the filter acts as a low pass filter when both switches are closed.

4. The filter of Claim 1, wherein multiple filter elements are used.

5. The filter of Claim 1, wherein the filter element and micro-electro-mechanical system switches are manufactured in one process.

6. A filter comprising:
at least one filter element having a central metal segment;
a first micro-electro-mechanical system switch associated with a first end of the central metal segment;
a second micro-electro-mechanical system switch associated with a second end of the central metal segment; and
wherein the position of the first micro-electro-mechanical system switch and the second micro-electro-mechanical system switch determines the filter characteristic.

7. The filter of Claim 6, wherein the first micro-electro-mechanical system switch and the second micro-electro-mechanical system switch are operable to connect the central metal segment with a first capacitor and a second capacitor when in a closed position.

8. The filter of Claim 7, wherein the filter is a band pass filter when the first micro-electro-mechanical

system switch and the second micro-electro-mechanical system switch are in an open position.

9. The filter of Claim 8, wherein the filter is a band pass filter with the pass zone in a lower frequency when the first micro-electro-mechanical system switch and the second micro-electro-mechanical system switch are in a closed position.

10. The filter of Claim 6, wherein the first micro-electro-mechanical system switch and second micro-electro-mechanical system switch are operable to connect a signal input line and a signal output line with the central metal segment.

11. The filter of Claim 10, wherein the filter is a band pass filter when the first micro-electro-mechanical system switch and the second micro-electro-mechanical system switch are in an open position.

12. The filter of Claim 10, wherein the filter is a band pass filter when the first micro-electro-mechanical system switch and the second micro-electro-mechanical system switch are in a closed position.

13. A tunable filter comprising:
at least one filter segment having a center metal segment;
a first capacitor formed on the signal line;
a second capacitor formed on the signal line;
a first micro-electro-mechanical system switch operable to connect the first capacitor with the center metal segment;
a second micro-electro-mechanical system switch operable to connect the second capacitor with the center metal segment; and
Wherein the position of the micro-electro-mechanical system switches determines the frequency response of the filter.

14. The filter of Claim 13, wherein the filter is a band pass filter when the first micro-electro-mechanical system switch and second micro-electro-mechanical system switch are in an open position.

15. The filter of Claim 14, wherein the filter is a band pass filter with the pass zone in a lower frequency when the first micro-electro-mechanical system switch and second micro-electro-mechanical system switch are in a closed position.

16. The filter of Claim 13, wherein the capacitors and the micro-electro-mechanical system switches are manufactured in the same process as the filter segment.

17. A filter comprising a coplanar waveguide filter element associated with micro-electro-mechanical system switches.

18. The filter of Claim 17, wherein the state of the micro-electro-mechanical system switches determines the properties of the filter.

19. The filter of Claim 18, wherein the filter is a band pass filter when the micro-electro-mechanical system switch is in a first position and the filter acts as a low pass filter when the micro-electro-mechanical system switch is in a second position.

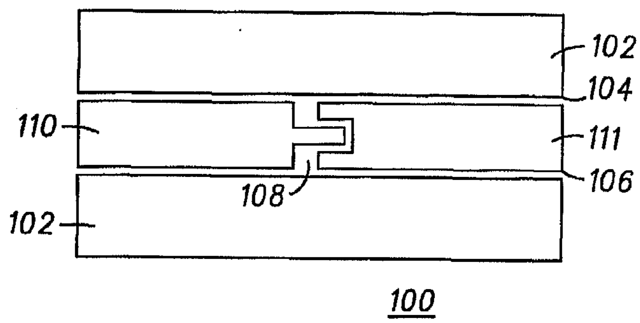


FIG. 1

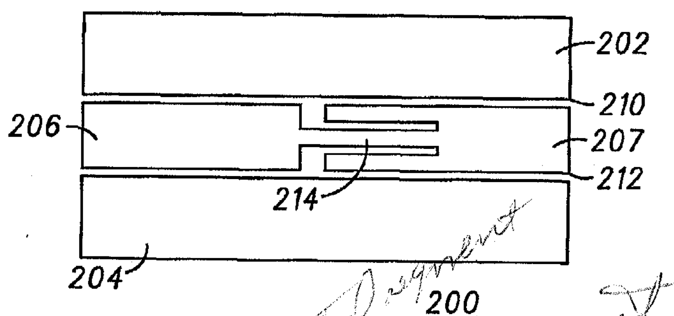


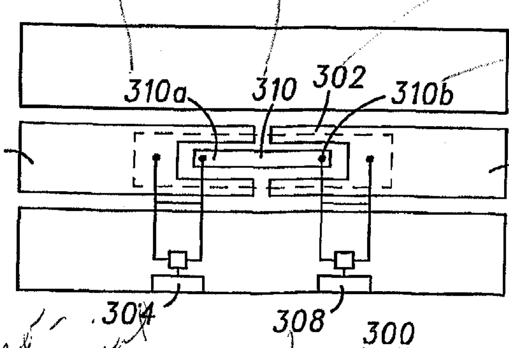
FIG. 2

1st part of central segment

central segment

Filter element

2nd part of central segment



signal input line

signal output line

1st micro-electro mechanical systems switch

2nd micro electro mechanical system switch

FIG. 3

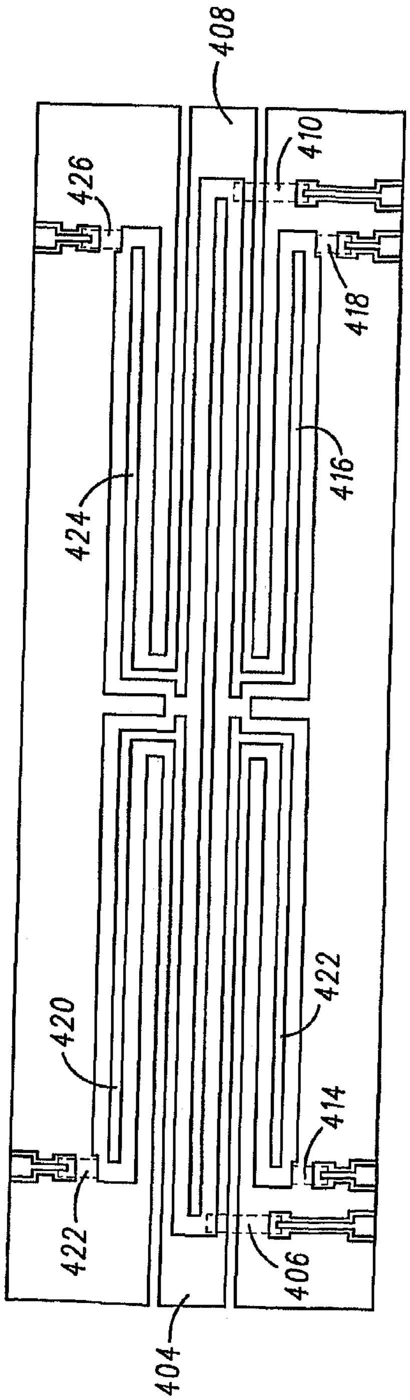


FIG. 4 402

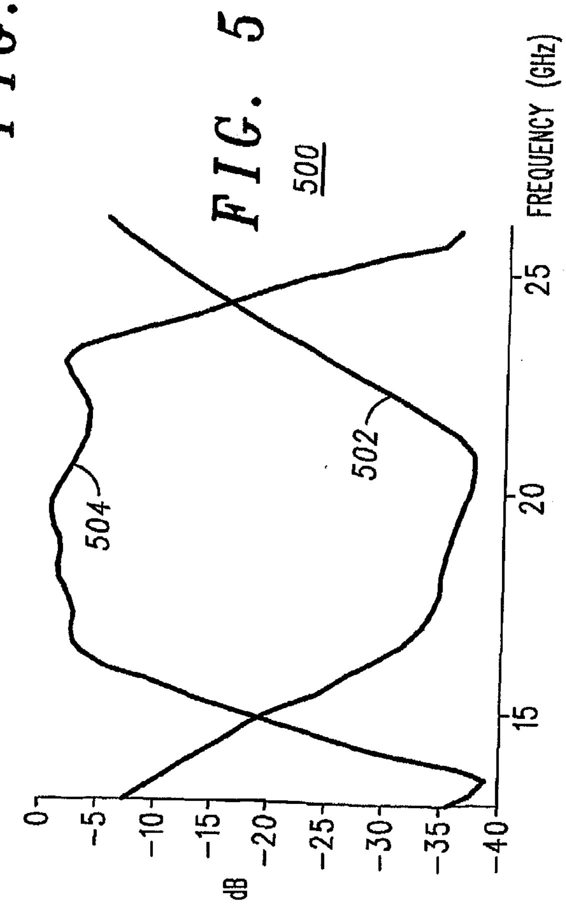


FIG. 5
500

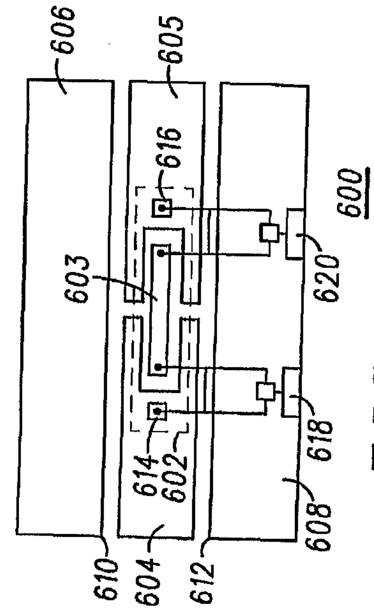


FIG. 6
600

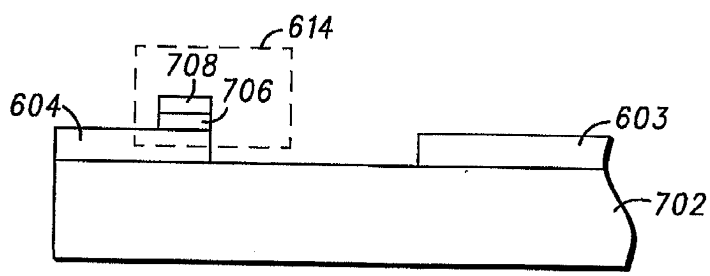
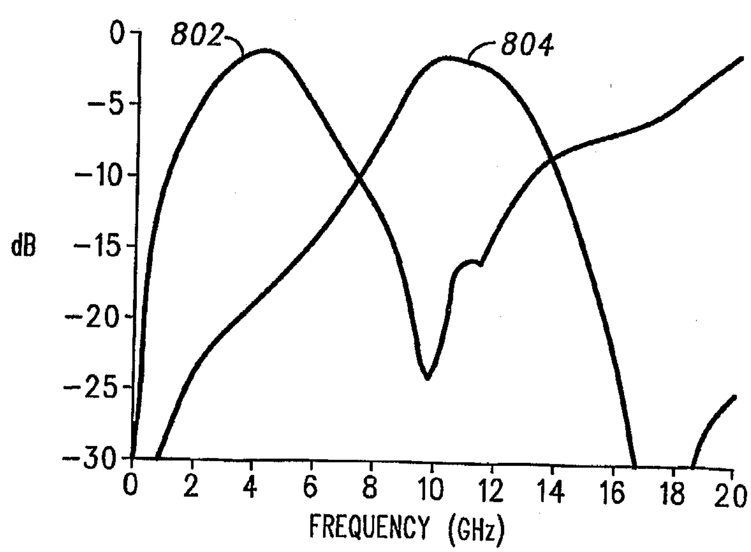


FIG. 7



800

FIG. 8

INTERNATIONAL SEARCH REPORT

Interr ıl Application No
PCT/US 01/25876

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01P1/201

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01P H01H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

PAJ, EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PEROULIS D ET AL: "MEMS DEVICES FOR HIGH ISOLATION SWITCHING AND TUNABLE FILTERING" 2000 IEEE MTT-S INTERNATIONAL MICROWAVE SYMPOSIUM DIGEST. IMS 2000. BOSTON, MA, JUNE 11-16, 2000, IEEE MTT-S INTERNATIONAL MICROWAVE SYMPOSIUM, NEW YORK, NY: IEEE, US, vol. 2 OF 3, 11 June 2000 (2000-06-11), pages 1217-1220, XP000967335 ISBN: 0-7803-5688-8 page 1219, right-hand column, line 9 -page 1220, right-hand column, line 5; figures 5,6	17,18
Y		19
A		1,6,13

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[X] Further documents are listed in the continuation of box C.

[ ] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 November 2001	26/11/2001

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Den Otter, A

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Interr al Application No
PCT/US 01/25876

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
Y	DIB N I ET AL: "COPLANAR WAVEGUIDE DISCONTINUITIES FOR P-I-N DIODE SWITCHES AND FILTER APPLICATIONS" MTT-S INTERNATIONAL MICROWAVE SYMPOSIUM DIGEST. DALLAS, MAY 8 - 10, 1990, NEW YORK, IEEE, US, vol. 1, 8 May 1990 (1990-05-08), pages 399-402, XP000143916 page 399, left-hand column, line 27-34; figure 1	19
A		1,6,13

X	MULDAVIN ET AL.: "X-BAND TUNABLE MEMS RESONATORS" 2000 TOPICAL MEETINGS ON SILICON MONOLITHIC INTEGRATED CIRCUITS IN RF SYSTEMS - DIGEST OF PAPERS, 26 - 28 April 2000, pages 116-118, XP010379874 Garmisch (DE) page 116, right-hand column, line 10 -page 117, right-hand column, line 2; figures 1-5 * abstract *	17,18
A		1,6,13
